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**PRESSURE-SENSITIVE-PAINT
MEASUREMENTS IN A
COMMERCIAL JET-ENGINE TEST
STAND**



**Jeffrey D. Jordan, A. Neal Watkins, John C. P. N. Davis,
and William L. Weaver**

**Innovative Scientific Solutions, Inc.
2766 Indian Ripple Road
Dayton, OH 45440-3638**

Gary A. Dale and Kelly R. Navarra (AFRL/VAOT)

Justin R. Urban, Wayne E. Devoid, and Richard A. Strange (Pratt & Whitney)

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WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7542**

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_____/s/_____
Gary A. Dale
Project Manager
AFRL/VAOT

_____/s/_____
Michael L. Zeigler
Chief, Technology Integration Branch
Integration & Operations Division

_____/s/_____
Jeffrey S. Turcotte, LTC, USAF
Chief
Integration & Operations Division

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Jeffrey D. Jordan, A. Neal Watkins, John C. P. N. Davis, and William L. Weaver
Innovative Scientific Solutions, Inc.
2766 Indian Ripple Road
Dayton, OH 45440-3638

Gary A. Dale and Kelly R. Navarra
Air Force Research Laboratory
Wright-Patterson AFB, OH 45433

Justin R. Urban, Wayne E. Devoid, and Richard A. Strange
Pratt & Whitney
400 Main St., M/S 121-02
East Hartford, CT 06108

ABSTRACT

This paper presents the application of pressure-sensitive paint (PSP) measurement technology to a large-scale commercial turbine-engine test stand. In this work, the test article is the engine-inlet bell mouth. A sol-gel-based PSP is applied to the inlet and illuminated using the blue (460-nm) output of eleven LED arrays. PSP data are acquired using a scientific-grade CCD camera. The application of PSP measurements in the engine-test-stand environment requires test instrumentation to be fixed within a housing located upstream of the test article. Challenges associated with performing PSP measurements in this hostile environment are discussed, with focus on the strategies implemented to recover surface-pressure distributions on the engine-inlet bell mouth.

INTRODUCTION

The accurate determination of spatially continuous pressure and temperature distributions on aerodynamic test surfaces is critical for the understanding of complex-flow mechanisms and high-cycle-fatigue (HCF)-related phenomena and for comparison with computational-fluid-dynamics (CFD) predictions. Conventional pressure measurements are based on pressure taps and electronically scanned transducers. Although these approaches provide accurate pressure information, pressure taps are limited to providing data at discrete points. In addition, integration of an adequate population of taps on a test surface can be time consuming, labor intensive, and expensive.

The ability to make an accurate determination of pressure and temperature distributions over an aerodynamic surface based on the emitted luminescence signal from a coating has attracted much attention in the aerospace community [1-14]. PSP measurements exploit the oxygen (O_2) sensitivity of luminescence probe molecules dispersed within gas-permeable binder materials. The mechanism for temperature-sensitive-paint (TSP) sensitivity is based on thermal-deactivation processes inherent in the probe species and temperature-dependent viscosity changes of the binder [15].

If the test surface under study is surrounded by an

atmosphere containing O₂ (e.g., air), the experimental intensity (I) and lifetime (τ) can be described as a function of O₂ partial pressure (P_{O2}) and the pressure exerted on the test surface within a Stern-Volmer framework [15]

$$\frac{\tau_0}{\tau} = \frac{I_0}{I} = 1 + K_{SV} P_{O_2} = 1 + k_q \tau_0 P_{O_2} \quad (1)$$

In this expression I and τ represent the luminescence intensity and the excited-state lifetime at a given P_{O2}, respectively. The subscript 0 denotes measurements in the absence of quencher (vacuum). K_{SV} is the Stern-Volmer quenching constant that provides a measure of the sensitivity of the luminescent species to O₂. The bimolecular quenching constant (k_q) reflects the quenching-process efficiency.

For intensity-based pressure measurements, it is often convenient to use a modified form of the Stern-Volmer expression that replaces the vacuum calibration (i.e., 0) with a reference standard

$$\frac{I_{ref}}{I} = A(T) + B(T) \frac{P}{P_{ref}} \quad (2)$$

In this approach, the reference intensity (I_{ref}) at a given reference pressure (P_{ref}) is divided by the luminescence intensity (I) at some test condition (P) over the region of interest. The coefficients A and B are determined experimentally for a given paint formulation and are a function of temperature (T). Calibration of this intensity ratio (I_{ref}/I) is then correlated with the output of a two-dimensional detector. In practice, the intensities are generally sampled over the surface of interest by a detector array such as a charge-coupled-device (CCD) camera. With today's CCD cameras having a million or more pixels, this technique provides a spatially continuous surface-pressure measurement with unequaled spatial resolution. The output of the CCD array can be visually represented as a two-dimensional image, with the luminescence corresponding to a gray or false-color scale.

The salient criteria that determine paint selection include output intensity, pressure and temperature sensitivity and stability, ease of application and removal, hazardous-material concerns, frequency response, and surface roughness. These characteristics are considered when developing a paint for a given application.

We have pursued the development of paints based on sol-gel-derived thin-film technology. Application of

sol-gel-derived composites to PSP technology offers several attractive features. First, sol-gel-derived coatings are characterized by high thermal stability and, therefore, exhibit very low temperature-dependent viscosity changes. Second, the aerosol-based deposition technique allows the formation of thin, uniform films that are optically transparent, robust, and smooth [13]. Furthermore, these coatings can be easily removed by destabilizing the base coat with a mild solvent (e.g., alcohol), which leaves the test surface unaffected. Third, sol-gel thin films exhibit excellent loading capabilities, allowing multiple probe species to be incorporated into the same film at high concentration for increasing output signals. Finally, novel thin-film architectures have been designed that provide a convenient means of optimizing the sensitivity of these composite coatings for the specific pressure and temperature regimes of interest.

In-Situ Calibration

To minimize temperature effects, pressure-tap data are often correlated with the intensity-ratio values of the surface-coated PSP. In this fashion, the tap data correct for illumination and temperature effects inherent in the PSP signal. To demonstrate the capability of this approach under low-speed-flow conditions, a sol-gel-based PSP was tested in the 0.3-m wind tunnel at NASA Langley Research Center in Hampton VA, which is used for testing two-dimensional airfoil sections and other models at high Reynolds numbers. This test was run under ambient-temperature air at low speed (M < 0.5). The model was a supercritical airfoil. A platinum meso-tetra (pentafluorophenyl) porphine [Pt(TfPP)]-based sol-gel low-speed PSP was applied to a portion of the model, with nine registration marks subsequently being drawn on the paint with permanent marker, as shown in Figure 1.

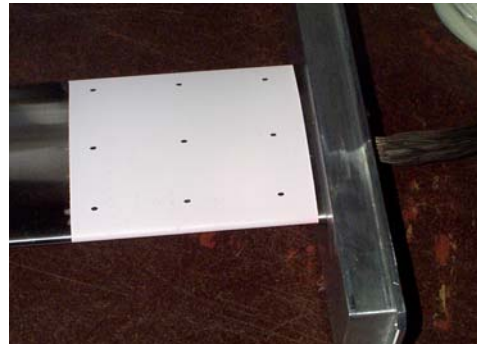


Figure 1. Pt(TfPP)-based sol-gel PSP applied to a model in the 0.3-m wind tunnel at NASA Langley.

Images were acquired using a 512 x 512 14-bit CCD camera with the model at 10° alpha under wind-off conditions and at Mach numbers of 0.15, 0.25, and 0.50 (ambient air). The data were analyzed by Langley personnel using a commercially available software package and the in-situ calibration method; the results are shown in Figure 2.

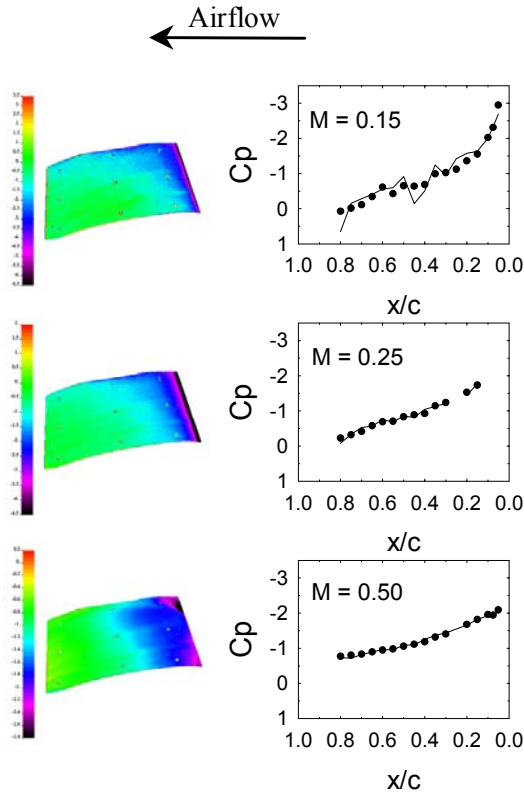


Figure 2. Pressure distribution across chord of SC3 model at three velocities.

The plots to the right of each image show a comparison of the pressure coefficient (C_p) recovered from the pressure tap (points) and PSP data (line). Good correlation was observed at $M = 0.25$ and 0.50 , with slight deviation at the lowest velocity investigated ($M = 0.15$), demonstrating the capability of PSP-based techniques for the measurement of 2D surface-pressure distributions at low velocity.

These results illustrate the utility of PSP measurements for the investigation of low-speed-flow aerodynamics. Transitioning this technology to the large-scale engine test cell introduces several additional challenges associated with the high-mass flow, high vibration, and large source-to-target distances. The remaining sections of this paper will discuss the strategies and mechanisms

employed to recover accurate surface-pressure distributions in this relatively hostile environment.

TEST SETUP

The deployment of PSP measurements in an engine test cell required two phases of setup: 1) model preparation and painting and 2) instrumentation installation and alignment. The following subsections summarize the steps taken to deploy PSP measurements within an engine test cell at Pratt & Whitney, East Hartford, CT.

PSP Application

A photograph of the engine-inlet bell mouth in the test cell is shown in Figure 3.

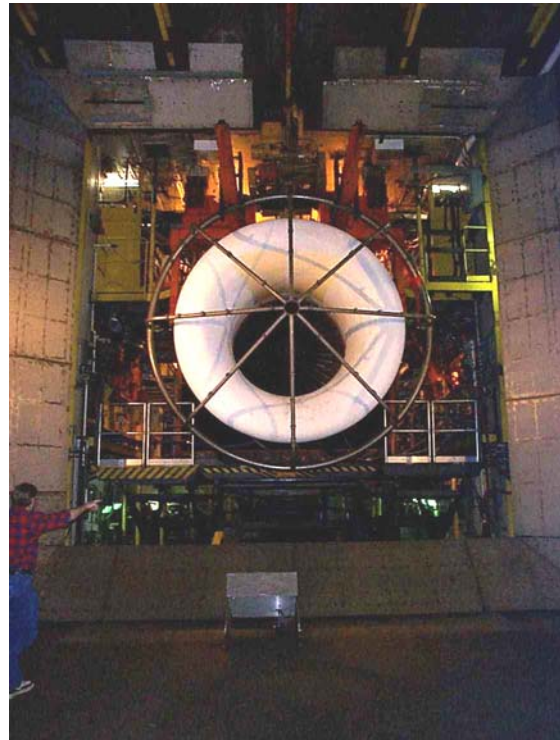


Figure 3. Engine-inlet bell mouth within test cell.

The internal diameter of the bell mouth tested was ~ 75 in. (1.9 m). The circular structure located upstream of the engine inlet (wagon wheel) was used to mount thermocouples. For this test, two symmetrical regions of the upper surface of the bell mouth were painted with a low-speed sol-gel-based PSP as shown in Figure 4.

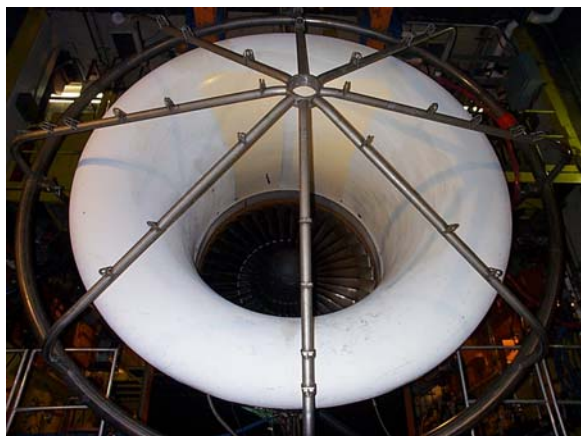


Figure 4. Painted engine-inlet bell mouth from the instrumentation housing (22 ft).

Prior to PSP application, the engine-inlet surface was first cleaned with alcohol and a lint-free cloth. The surrounding area was then masked to prevent overspray from contacting the unpainted areas of the bell mouth, the fan blades, the pressure transducers, and the wagon-wheel structure located upstream of the inlet. A white base coat was applied and allowed to dry for ~1 hr prior to deposition of the sol-gel PSP. Finally, registration (fiducial) marks were drawn on the painted surface in a grid formation and the precise locations determined using a coordinate mapping system (CMS). These data allow reference images acquired under isobaric and isothermal conditions (wind off) to be registered and accurately ratioed with the spatially distorted images acquired at condition (wind-on).

Hardware Installation

The high-mass flow encountered within large-scale engine test cells requires that precautionary measures be taken to prevent the ingestion of diagnostic instrumentation components that would cause engine damage and/or catastrophic failure. To that end, the housing structure shown in Figure 5 was designed and constructed by Pratt & Whitney personnel.

The instrumentation housing was designed to support the mounting of eleven LED-based illumination sources and a scientific-grade CCD camera and controller (16-bit, 512 x 512, back-lit, slow-scan CCD). The individual lamp mounts allowed each unit to be rotated and translated within the structure for alignment purposes.



Figure 5. LED lamps and CCD camera being installed within the instrumentation housing (upper) and in operation (lower).

Once installed and aligned, a transparent shield (0.5-in. thick) was installed within a groove in the housing to isolate the instrumentation from the flow. The housing structure was mounted on two, 3-ft I-beam sections that were bolted to the test-cell floor at a distance of ~22 ft (6.7 m) from the PSP-coated surface. Cables were run from a cutout in the back of the housing to the LED-array power supply that was located aft of the engine inlet.

The LED-lamp output was controlled using a break-out box wired to the control room. The CCD camera was operated remotely via a fiber-optic serial interface.

EXPERIMENTAL PROCEDURE

Steady-state PSP data were acquired under three experimental conditions: 1500, 6000, and 10000 lb of thrust. Single-shot PSP images were also acquired while the engine thrust was ramped from 6000 to 26,000 lb to acquire dynamic pressure changes during transition. During steady-state test operation, PSP, pressure tap, and thermocouple data were acquired simultaneously. Fifteen PSP and background (lamp-off) images were collected at each run condition for later post processing.

DATA ANALYSIS

PSP Image Registration

Image registration is an area of active research in the PSP community. Currently deployed PSP systems require that intensity (I) images collected at condition (wind-on) be ratioed to images collected at an isobaric (wind-off) condition ($I_{\text{wind-off}} / I_{\text{wind-on}}$). Test-article deflection and warping between the wind-on and wind-off conditions result in systematic errors in the calculated intensity ratio. Identical image locations on the model rather than identical CCD camera pixel locations must be ratioed.

In practice, image processing for paint-sensor systems falls into two categories--image registration and image resection. Image registration is concerned with the effects of model movement and deformation on the calculation of the $I_{\text{wind-off}}/I_{\text{wind-on}}$ ratio; image resection involves the accurate placement of the resulting two-dimensional image of pressure values on a three-dimensional wire-mesh model grid for spatial quantitative visualization. Algorithms for image registration and image resection in the area of PSP appear in the published literature [16, 17]. For simple image translation, x and y coordinates of a given pixel in the wind-on image are related to the pixel coordinates of the identical model location in the wind-off image (x' and y') through the transforms in Eq. 3, where m is a magnification factor and s_x and s_y represent the x and y components of the shift, respectively.

$$x = R_x(x', y') = mx' + s_x \quad (3a)$$

$$y = R_y(x', y') = my' + s_y \quad (3b)$$

To account for model bending, Eq. 3 is extended to a set of second-order equations appearing in Eq. 4.

$$x = \sum_{i,j=0}^2 a_{i,j} x'^i y'^j \quad (i+j \leq 2) \quad (4a)$$

$$y = \sum_{i,j=0}^2 b_{i,j} x'^i y'^j \quad (i+j \leq 2) \quad (4b)$$

The coefficients $a_{i,j}$ and $b_{i,j}$ can be determined by using at least six pairs of known image locations in the wind-off and wind-on images [(x,y),(x',y') pairs] and solving for the coefficients using a least-squares fitting

algorithm. These image locations are typically well-defined model features or registration marks placed on the model. After the coefficients have been determined, the shifted x and y pixel coordinates are calculated, and the pixel values of the registered wind-on image are calculated by linear interpolation of the pixel intensities in the actual wind-on image. The intensity ratio of the $I_{\text{wind-off}}$ to the registered $I_{\text{wind-on}}$ yields the corrected values.

The process of image resection has its basis in the area of photogrammetry [18-21]. Image resection is the process of recovering the three-dimensional coordinates of a surface from a two-dimensional image of the surface. This process is used in the PSP technique for accurate placement of the calculated pressure values on a three-dimensional wire-mesh model of the test article to extract three-dimensional quantitative surface-pressure information. Bell and McLachlan [17] have demonstrated the utility of the Direct Linear Transform (DLT) [21] formulation for the process of image resection. The x and y coordinates of the two-dimensional CCD-camera image are translated into X, Y, and Z model coordinates via Eq. 5.

$$x = \frac{L_1 X + L_2 Y + L_3 Z + L_4}{L_9 X + L_{10} Y + L_{11} Z + 1} \quad (5a)$$

$$y = \frac{L_5 X + L_6 Y + L_7 Z + L_8}{L_9 X + L_{10} Y + L_{11} Z + 1} \quad (5b)$$

The 11 DLT unknown coefficients in Eq. 5 can be determined using the same six pairs of registration marks that were used for image registration. Information required from the six pairs is the X, Y, and Z coordinates of the registration marks in model space and the two-dimensional x, y coordinates of the registration marks in the CCD-camera image. The location of the x, y pixel coordinates is obtained from inspection of the CCD-camera image. The X, Y, Z model coordinates are obtained independently using a CMS. Armed with the six registration marks of known 2-D and 3-D coordinates, one can uniquely determine the coefficients in Eq. 5 by solving the resulting system of linear algebraic equations.

QPED Registration Method

We are currently investigating the development of new algorithms to aid in the image-registration process. The study involves evaluating the utility of automated techniques that have potential for performing image

registration in an unattended and non-user-assisted algorithm. The algorithm under development is called Quantum Pixel Energy Distribution (QPED) [22]. This algorithm is based on the discrete pixel-based architecture of the CCD camera and is intended to augment the linear-interpolation algorithm used for fractional-pixel image shifting.

The QPED process is used as the foundation for an optimizing search algorithm. In this algorithm, a matrix of x , y shift values for each pixel (QPED matrix) in a wind-off image are adjusted on a pixel-by-pixel basis. The resulting pixel-shifted image (QPED image) is ratioed with the wind-on image, and the quality of the resulting intensity-ratio image is assessed. The QPED matrix values are adjusted until the optimal condition is found.

For the present experiments, the QPED algorithm was used for image registration and the results compared with those obtained using the registration functions included in the commercially available PSP data-reduction software.

RESULTS

Figure 6 shows the engine inlet bell mouth under illumination from the 11 LED sources located within the instrumentation housing (image lower left).



Figure 6. Engine inlet illuminated using 11 LED-based illumination sources at a distance of 22 ft.

During PSP data acquisition, all non-essential test-cell lights were turned off to mitigate background. For PSP data post processing, the ground-idle condition was used as the wind-off reference and ratioed with the images acquired under each test condition. To facilitate the resection of PSP data to a three-dimensional grid, the commercially available software package maps the two-dimensional CCD image acquired under each test condition to the wind-off data. The QPED algorithm maintains the capability of using either condition as the target, and for these experiments mapped the static wind-off data to the wind-on images. This practice allows visualization of the aerodynamic-load-induced deformation of the test article. The left-hand portion of the painted regions was obscured under test conditions and was removed from the image. A CFD grid was not available to allow image resection to a three-dimensional model. Pressure data were available from a single tap located on the surface of the bell mouth near the fan. The pressure results at this point were correlated with the intensity-ratio data from the PSP, providing a one-point in-situ calibration. This analysis was performed for a single PSP image

acquired at the 10,000-lb thrust condition, and the results are shown in Figure 7.

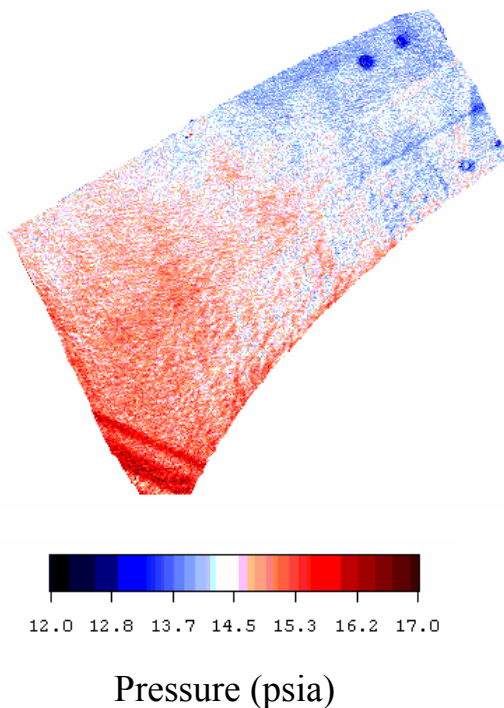


Figure 7. PSP image at 10000 lb of thrust corrected using a single-point in-situ calibration.

The PSP image shows that the pressure near the leading edge in the stagnation region is consistent with the ambient pressure (~14.8 psia) in the test cell. The pressure decreases with increasing velocity as the flow is accelerated through the inlet toward the engine fan. The total recovered pressure differential from the bell mouth leading to the trailing edge is ~1.2 psi. The striped region in the image lower left corresponds to a shadow from the wagon wheel that was not removed in the post processing.

PSP images acquired as the engine was accelerated through 26,000 lb of thrust were registered using the QPED algorithm and ratioed with the images acquired under ground idle; four of these are shown in Figure 8.

The intensity-ratio images range in thrust from 13,000 to 26,000 lb. Intensity ratios greater than one indicate

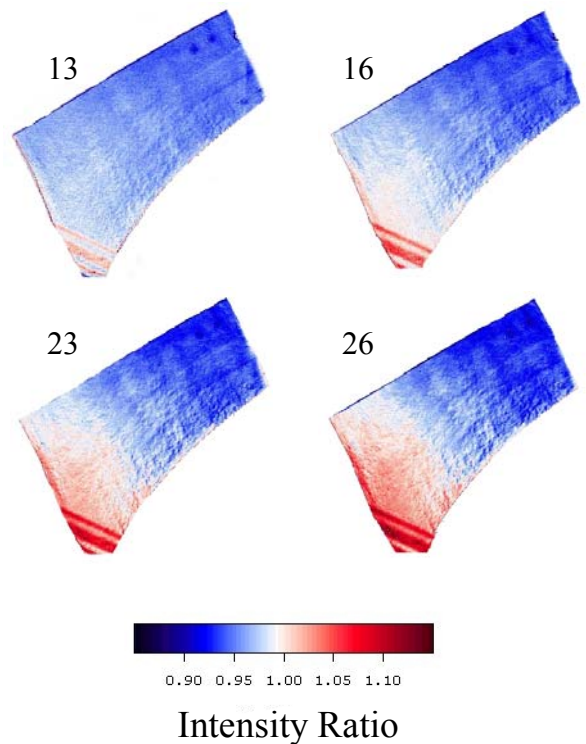


Figure 8. PSP intensity-ratio images as a function of thrust (/1000 lb).

higher than ambient pressures and/or temperatures, and vice versa for values lower than one. The scales presented in Figures 7 and 8 are not the same. For these tests, pressure-tap data were not acquired; this prevented the application of in-situ calibration methods. Nonetheless, it is clear from these data that as the engine thrust increases, the magnitude of the pressure/temperature distributions increases on both the leading and trailing edges. Together these results show the feasibility of performing PSP measurements using LED-based illumination sources in large-scale test-engine environments.

The registration capabilities of the newly developed QPED algorithm were compared to the standard registration functions utilized in the commercially available software using data acquired at 26,000 lb of thrust. Figure 9 shows the two ratioed images on identical scales.

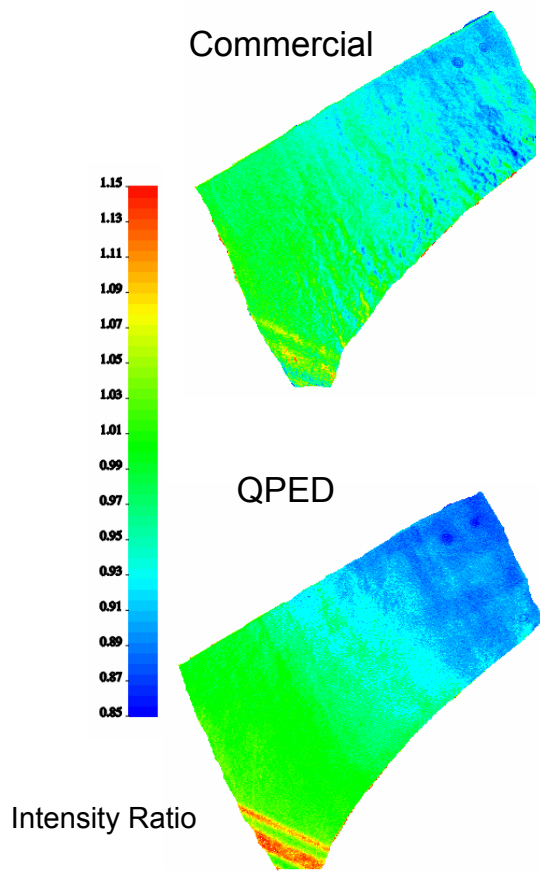


Figure 9. PSP intensity-ratio images at 26,000 lb of thrust registered using commercially available (top) and QPED (bottom) software.

It should be noted that of the twelve registration marks placed on the painted area, only seven were visible to the camera; model displacement during operation caused them to be obscured by the wagon wheel. The QPED registration was accomplished without the use of registration targets with known x, y, z positions. Image features including pressure taps, edges, and surface topography were used to register the images.

SUMMARY

To our knowledge, these results represent the first successful deployment of PSP measurements in a large-scale commercial-engine test stand. Challenges associated with the high source-to-target distances (22 ft), the high mass flow, severe vibration, and large test-article displacement between the wind-off and wind-on conditions were overcome to recover surface-pressure

distributions on an engine-inlet bell mouth. Current efforts focus on the development of PSPs that contain an additional probe species that is sensitive to temperature only. These paints will provide a means of decoupling the effects of pressure and temperature in PSP measurements without pressure-tap data being necessary to perform in-situ calibration. Additional efforts are focused on optimizing PSPs and measurement techniques for rotating turbomachinery components in the latter stages of the turbine engine.

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